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Comparisons of HVAC Simulations between EnergyPlus and DOE-2.2 for Data Centers

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Environmental Energy Technologies Division

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Disclaimer

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ABSTRACT

This paper compares HVAC simulations between EnergyPlus and DOE-2.2 for data centers. The HVAC systems studied in the paper are packaged direct expansion air-cooled single zone systems with and without air economizer. Four climate zones are chosen for the study - San Francisco, Miami, Chicago, and Phoenix. EnergyPlus version 2.1 and DOE-2.2 version 45 are used in the annual energy simulations. The annual cooling electric consumption calculated by EnergyPlus and DOE-2.2 are reasonablely matched within a range of -0.4% to 8.6%. The paper also discusses sources of differences beween EnergyPlus and DOE-2.2 runs including cooling coil algorithm, performance curves, and important energy model inputs.

INTRODUCTION

Data centers although representing a small fraction of the total commercial building stock, consume significant amounts of electricity, 25 to 50 times of standard offices, for IT equipment and space cooling due to 24 by 7 operation and high internal loads of up to 100 Watts per square foot or more. Energy simulation tools have been used to study energy conservation measures for data centers in order to reduce energy consumption. DOE-2.1E (LBNL 1993) and DOE-2.2 (Hirsch 2007) have been two popular tools used by the data center industry. With added capabilities of central plant modeling features, DOE-2.2 is replacing DOE-2.1E for data center applications.

EnergyPlus (USDOE 2007), on the other hand, is intended to replace DOE-2 as the next generation building simulation tool. EnergyPlus inherited most of the useful features from DOE-2 and BLAST, and more significantly added new modeling capabilities far beyond DOE-2, BLAST, and other simulations tools currently available. For a detailed comparison of modeling capabilities among EnergyPlus and 19 other tools, refer to the paper (Crawley 2005) which is available on the EnergyPlus web site www.energyplus.gov.

EnergyPlus has advantages over DOE-2.2 in the simulation of energy performance of data centers:

- EnergyPlus allows user defined loads calculation time step, from one minute up to 60 minutes per time step. The systems time step is automatically adjusted, downward from the loads time step, to obtain convergence solutions. Users can set a minimum of systems time step and a maximum of systems iteractions. DOE-2.2 can only allow hourly calculations for both loads and systems. Sub-hourly time step calculations may be necessary to better model HVAC systems and controls.
- EnergyPlus does the integrated solution of loads, systems, and plant to accurately calculate their interactions within the same time step; while DOE-2.2 does the sequential calculations from loads to systems to plant without feedback within the same time step.
- EnergyPlus allows dual-setpoint humidistat with deadband for zones to better control the zone air humidity. DOE-2.2 only allows input of the maximum relative humidity setpoint of the return air at the system level. Humidity control can be a key issue for data centers in dry or moist climates.
- EnergyPlus can model integrated water economizer at the plant level while DOE-2.2 cannot. Integrated water economizer uses two stage of cooling: first with cool condernser water from the cooling tower, then with chilled water from chillers to meet system remaining cooling

loads. Integrated water economizer can be an energy efficient measure (free cooling) for data centers located in cool or dry climates.

- EnergyPlus can model underfloor air distribution (UFAD) systems with multi-node temperatures to better represent the temperature stratification of room air. DOE-2.2 assumes well-mixed uniform room air temperature. UFAD is commonly used in data centers.
- EnergyPlus allows user-defined HVAC systems with flexible connections to water, air, and steam loops. DOE-2.2 can only model predefined hardwired HVAC systems.
- EnergyPlus allows multiple HVAC systems to serve a single zone while DOE-2.2 cannot. A data center may have multiple CRAC (Computer Room Air Conditioner) units to meet the cooling loads.

On the other hand, EnergyPlus models, especially with a large number of zones, run much slower than those of DOE-2.2. For data centers modeling, a few thermal zones would be adequate, therefore the EnergyPlus run time would not be an issue. It may also take more time and effort to create EnergyPlus energy models than DOE-2.2 due to EnergyPlus' complex input data file structure. Fortunately commercial software are available and getting more powerful to help users quickly create EnergyPlus models.

EnergyPlus has been tested with several test suites including:

- Analytical Tests
  - HVAC tests, based on ASHRAE Research Project 865
  - Building fabric tests, based on ASHRAE Research Project 1052
- Comparative Tests
  - ANSI/ASHRAE Standard 140-2004
  - International Energy Agency Solar Heating and Cooling Programme BESTest (Building Energy Simulation Test) methods
  - EnergyPlus HVAC Component Comparative tests
  - EnergyPlus Global Heat Balance tests

These test reports are available at EnergyPlus web site. Very few public reports are available that compare results between EnergyPlus and DOE-2.2 on an apples-to-apples basis. EnergyPlus and DOE-2.2 have been tested with the ANSI/ASHRAE Standard 140-2004: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, which focuses on comparing the building envelope loads while assuming ideal constant efficiency HVAC systems. Huang (2006) performed comparisons of California Alternative Calculation Method (CEC 2004) accuracy tests with DOE-2.1E and EnergyPlus. While trying to match the results between two tools, Joe discovered quite a few interesting problems of both DOE-2.1E and EnergyPlus in terms of how they model things and how they interpret model inputs.

This paper focuses on comparing HVAC (Heating, Ventilating, and Air-Conditioning) simulations between EnergyPlus and DOE-2.2 for data center applications, specifically the packaged single zone systems with and without air economizer for four climate zones - San Francisco, Miami, Chicago, and Phoenix. The objectives of the comparisions are to:

- Demonstrate feasibility and usability of EnergyPlus for data center applications,
- Benchmarking results between EnergyPlus and DOE-2.2,
- Identify descrepancies between EnergyPlus and DOE-2.2 simulations, and
- Provide some guidelines for preparing and comparing EnergyPlus and DOE-2.2 simulations.

ENERGY SIMULATIONS

Description of Data Center Energy Models

The prototype data center is an interior box 100 feet wide by 100 feet long and 9 feet high. There are no exterior surfaces or windows. The operation schedule is 24 by 7 with a total of 8760 hours a year. IT equipment and lighting together have an equipment power density of 100 watts per square foot. Only one occupant resides in the data center. IT equipment and lighting are assumed to be 100% on all the time. The minimum amount of outside air is 1500 cfm (708 L/s), based on 0.15 cfm/ft^2 (0.07 L/s/m^2). The HVAC system is a packaged single zone (PSZ) direct expansion (DX) system with air-cooled condenser, constant speed supply fan, with conventional overhead air distribution, and without humidity control. The supply fan runs continually and has a static pressure of 2.52 in.wg (628 Pa) and 54% total efficiency. The cooling efficiency COP (Coefficient of Performance) excluding fan is 2.82. The supply fan has a draw-through configuration (downstream of the DX cooling coil). The DX coil has a rated cooling bypass factor of 0.05. The cooling setpoint is 76^{o}F (24.4^{o}C). The zone thermostat has a throttling range of 0.2^{o}F (0.1^{o}C). The supply air temperature is set to 55^{o}F (12.8^{o}C). The default DOE-2.2 performance curves for PSZ systems are used. These curves are converted into metric (SI) units for EnergyPlus use.

The HVAC system airflow and cooling capacity are autosized by DOE-2.2. The DOE-2.2 sizing results (total cooling capacity, sensible heat ratio, and supply air flow) in the SV-A report are then converted into SI units for input to EnergyPlus models.

The idea of using this simple data center model is to isolate complexity of building loads and other end uses so that the focus is on the HVAC system performance.

Description of Simulation Runs

There are a total of 16 simulation runs – 8 EnergyPlus runs and 8 DOE-2.2 runs. The EnergyPlus runs are done with EnergyPlus 2.1 released in October 2007. The DOE-2.2 runs are done with eQuest 3.61e which uses DOE-2.2 v45 as the calculation engine. The EnergyPlus runs are done with 15-minute time step while DOE-2.2 runs are with 1-hour time step. Four typical climate zones are studied - San Francisco (3C – Warm Marine), Miami (1A – Very Hot Humid), Chicago (5A – Cool Humid), and Phoenix (2B – Hot Dry). San Francisco climate has the most free cooling potential with air economizer, followed by Chicago, Phoenix, and Miami. The TMY2 weather files for the four locations are converted to the DOE-2 weather file format and used for the DOE-2.2 runs. These weather files are then converted into EnergyPlus epw files for the EnergyPlus runs. One set of runs are for HVAC systems without air economizer, while the other set with air economizer of dual enthalpy type (by comparing the enthalpy of the outside air with the enthalpy of the return air). The EnergyPlus runs use DX cooling performance curves directly converted from eQuest for the CCAP(EWB,ODB): total cooling capacity as a function of outside dry-bulb (ODB) and entering wet-bulb temperatures (EWB), the EIR(EWB,ODB): cooling efficiency (Energy-Input-Ratio) as a function of outside dry-bulb and entering wet-bulb temperatures, and the EIR(PLR): cooling efficiency as a function of part-load ratio (PLR).

Simulation Results

Table 1shows the annual end-use for the 16 EnergyPlus and DOE-2.2 runs. For monthly cooling electric consumptions, both data tables and figures are produced to compare results, as figures are helpful to visualize trend and big pictures while data tables can show detailed differences if multiple curves or data points get crowded or overlapped in the figures. Tables 2 to 9 and Figures 1 to 8 show the monthly cooling electric consumption for all the 16 EnergyPlus and DOE-2.2 runs.

Table 1 - Annual Energy End-Use between EnergyPlus and DOE-2.2

				Annual kWh			
Run ID	**Description**	**Location**	**Tool**	**Cooling**	**Fan**	**Equipment**	**Total**
SF-D-1	PSZ, Air-cooled, No economizer	San Francisco	DOE-2.2	2,757,204	872,274	8,760,000	12,389,478
SF-E-1	PSZ, Air-cooled, No economizer	San Francisco	EnergyPlus	2,751,225	873,675	8,760,000	12,384,900
		% Difference from DOE-2.2		-0.2%	0.2%	0.0%	0.0%
SF-D-1a	PSZ, Air-cooled, Airside Economizer	San Francisco	DOE-2.2	387,331	872,274	8,760,000	10,019,605
SF-E-1a	PSZ, Air-cooled, Airside Economizer	San Francisco	EnergyPlus	420,800	873,675	8,760,000	10,054,475
		% Difference from DOE-2.2		8.6%	0.2%	0.0%	0.3%
MI-D-1	PSZ, Air-cooled, No economizer	Miami	DOE-2.2	3,056,195	872,236	8,760,000	12,688,431
MI-E-1	PSZ, Air-cooled, No economizer	Miami	EnergyPlus	3,053,094	873,675	8,760,000	12,686,769
		% Difference from DOE-2.2		-0.1%	0.2%	0.0%	0.0%
MI-D-1a	PSZ, Air-cooled, Airside Economizer	Miami	DOE-2.2	2,831,250	872,236	8,760,000	12,463,486
MI-E-1a	PSZ, Air-cooled, Airside Economizer	Miami	EnergyPlus	2,838,642	873,675	8,760,000	12,472,317
		% Difference from DOE-2.2		0.3%	0.2%	0.0%	0.1%
CH-D-1	PSZ, Air-cooled, No economizer	Chicago	DOE-2.2	2,803,335	872,275	8,760,000	12,435,610
CH-E-1	PSZ, Air-cooled, No economizer	Chicago	EnergyPlus	2,793,883	873,675	8,760,000	12,427,558
		% Difference from DOE-2.2		-0.3%	0.2%	0.0%	-0.1%
CH-D-1a	PSZ, Air-cooled, Airside Economizer	Chicago	DOE-2.2	917,023	872,275	8,760,000	10,549,298
CH-E-1a	PSZ, Air-cooled, Airside Economizer	Chicago	EnergyPlus	918,878	873,675	8,760,000	10,552,553
		% Difference from DOE-2.2		0.2%	0.2%	0.0%	0.0%
PH-D-1	PSZ, Air-cooled, No economizer	Phoenix	DOE-2.2	3,132,159	872,603	8,760,000	12,764,762
PH-E-1	PSZ, Air-cooled, No economizer	Phoenix	EnergyPlus	3,119,722	873,675	8,760,000	12,753,397
		% Difference from DOE-2.2		-0.4%	0.1%	0.0%	-0.1%
PH-D-1a	PSZ, Air-cooled, Airside Economizer	Phoenix	DOE-2.2	2,097,189	872,603	8,760,000	11,729,792
PH-E-1a	PSZ, Air-cooled, Airside Economizer	Phoenix	EnergyPlus	2,089,808	873,675	8,760,000	11,723,483
		% Difference from DOE-2.2		-0.4%	0.1%	0.0%	-0.1%

Table 2 - Monthly Cooling Electricity Consumption for San Francisco Runs without Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	232,687	232,329	-0.2%
Feb	210,598	210,318	-0.1%
Mar	233,054	232,742	-0.1%
Apr	225,937	225,646	-0.1%
May	234,068	233,720	-0.1%
Jun	227,058	226,752	-0.1%
Jul	236,062	235,721	-0.1%
Aug	235,387	235,038	-0.1%
Sep	229,109	228,746	-0.2%
Oct	234,552	234,211	-0.1%
Nov	225,896	225,554	-0.2%
Dec	232,797	232,434	-0.2%

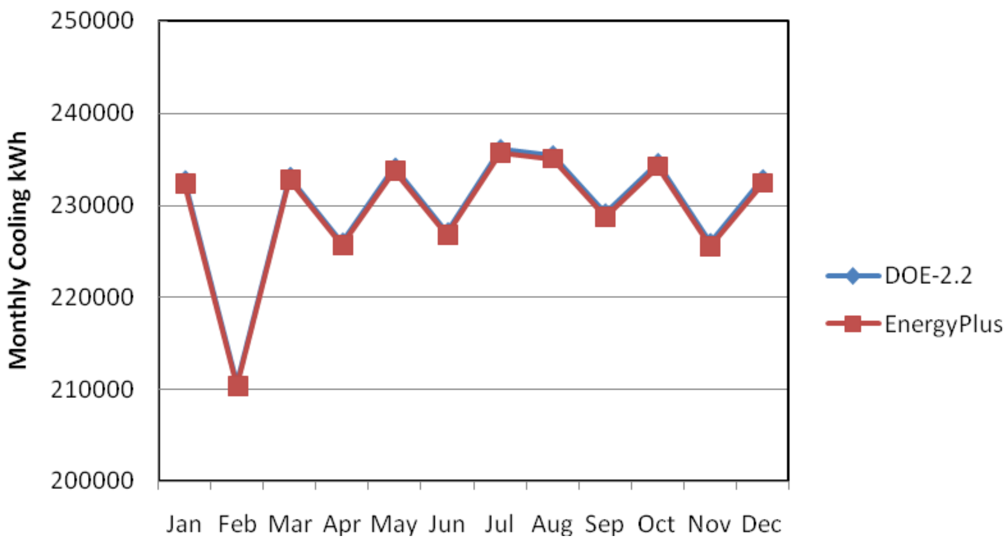

Figure 1 – Monthly Cooling Electricity Consumption for San Francisco Runs without Air Economizer

Table 3 - Monthly Cooling Electricity Consumption for San Francisco Runs with Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	1,465	1,322	-9.8%
Feb	8,338	9,423	13.0%
Mar	5,074	4,992	-1.6%
Apr	16,825	17,082	1.5%
May	36,644	38,830	6.0%
Jun	43,806	48,020	9.6%
Jul	63,182	71,840	13.7%
Aug	68,141	75,955	11.5%
Sep	79,567	85,018	6.9%
Oct	50,900	54,984	8.0%
Nov	12,883	13,928	8.1%
Dec	508	390	-23.1%

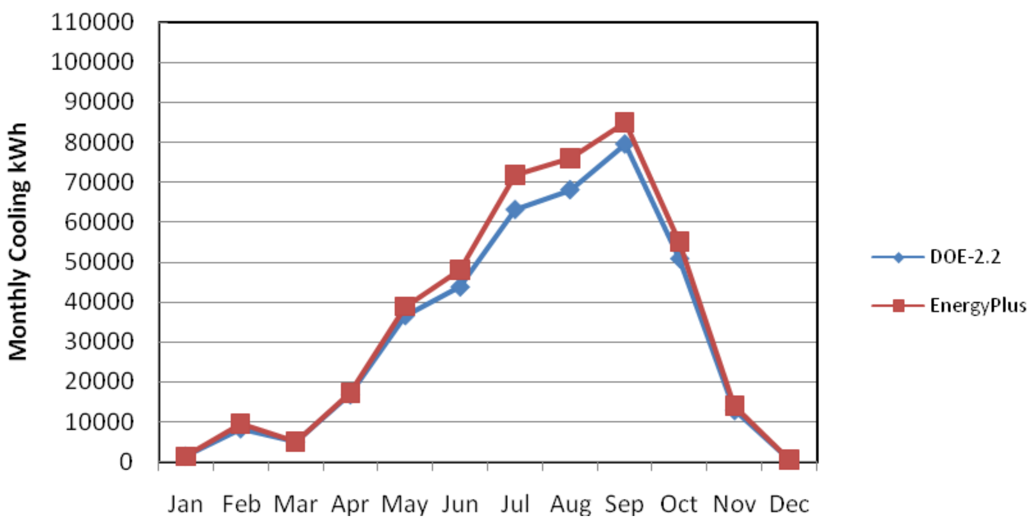

Figure 2 – Monthly Cooling Electricity Consumption for San Francisco Runs with Air Economizer

Table 4 - Monthly Cooling Electricity Consumption for Miami Runs without Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	243,506	243,495	0.0%
Feb	221,118	221,143	0.0%
Mar	246,997	247,101	0.0%
Apr	249,242	249,339	0.0%
May	265,048	265,043	0.0%
Jun	264,783	264,602	-0.1%
Jul	278,065	277,674	-0.1%
Aug	277,452	277,061	-0.1%
Sep	263,022	262,899	0.0%
Oct	261,035	261,152	0.0%
Nov	243,859	244,071	0.1%
Dec	242,068	242,049	0.0%

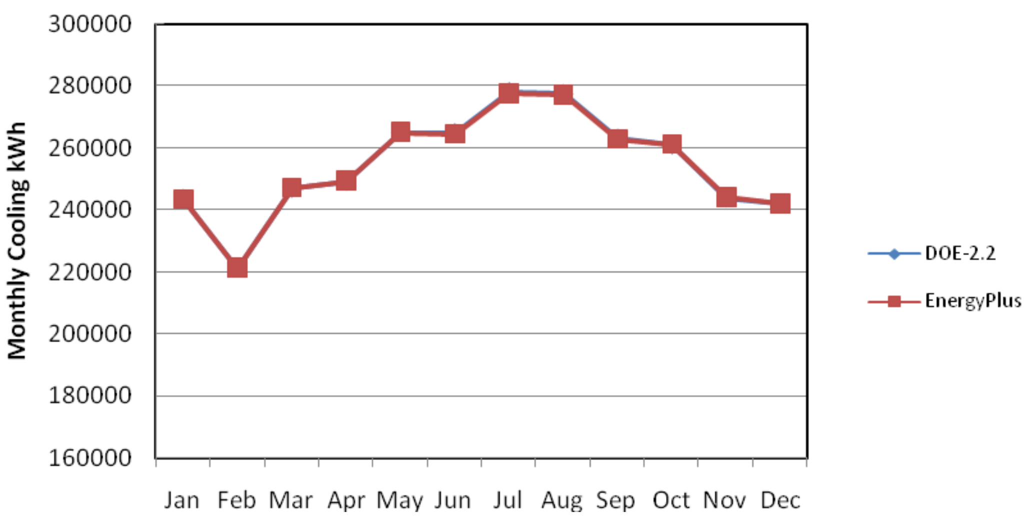

Figure 3 – Monthly Cooling Electricity Consumption for Miami Runs without Air Economizer

Table 5 - Monthly Cooling Electricity Consumption for Miami Runs with Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	188,948	190,457	0.8%
Feb	173,537	174,956	0.8%
Mar	201,946	203,577	0.8%
Apr	238,332	239,141	0.3%
May	264,915	264,946	0.0%
Jun	264,783	264,602	-0.1%
Jul	278,065	277,674	-0.1%
Aug	277,452	277,061	-0.1%
Sep	263,022	262,899	0.0%
Oct	259,190	259,582	0.2%
Nov	228,176	229,872	0.7%
Dec	192,885	196,597	1.9%

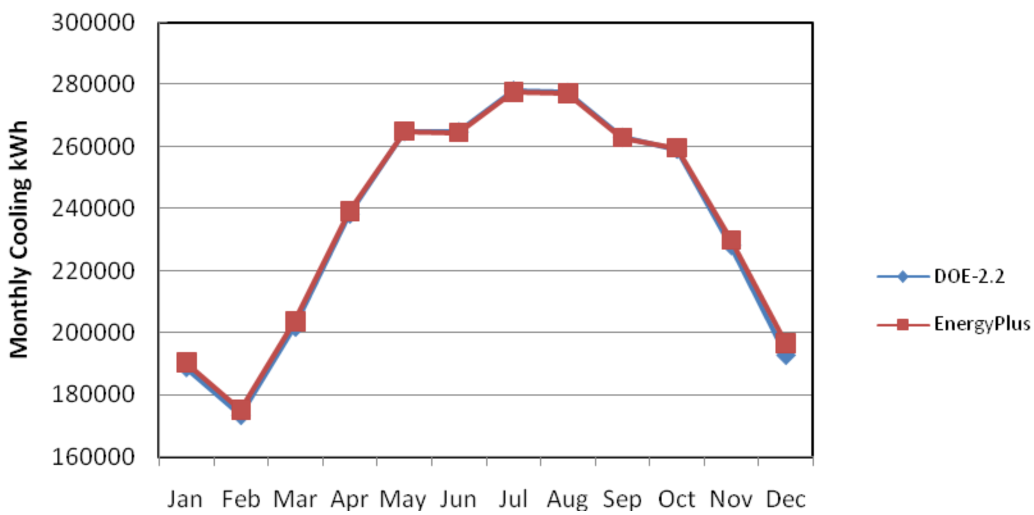

Figure 4 – Monthly Cooling Electricity Consumption for Miami Runs with Air Economizer

Table 6 - Monthly Cooling Electricity Consumption for Chicago Runs without Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	230,655	229,775	-0.4%
Feb	208,730	207,960	-0.4%
Mar	231,803	231,003	-0.3%
Apr	225,490	224,821	-0.3%
May	238,340	237,720	-0.3%
Jun	240,864	240,421	-0.2%
Jul	256,065	255,790	-0.1%
Aug	248,556	248,283	-0.1%
Sep	232,501	232,001	-0.2%
Oct	234,356	233,683	-0.3%
Nov	224,943	224,223	-0.3%
Dec	231,032	230,180	-0.4%

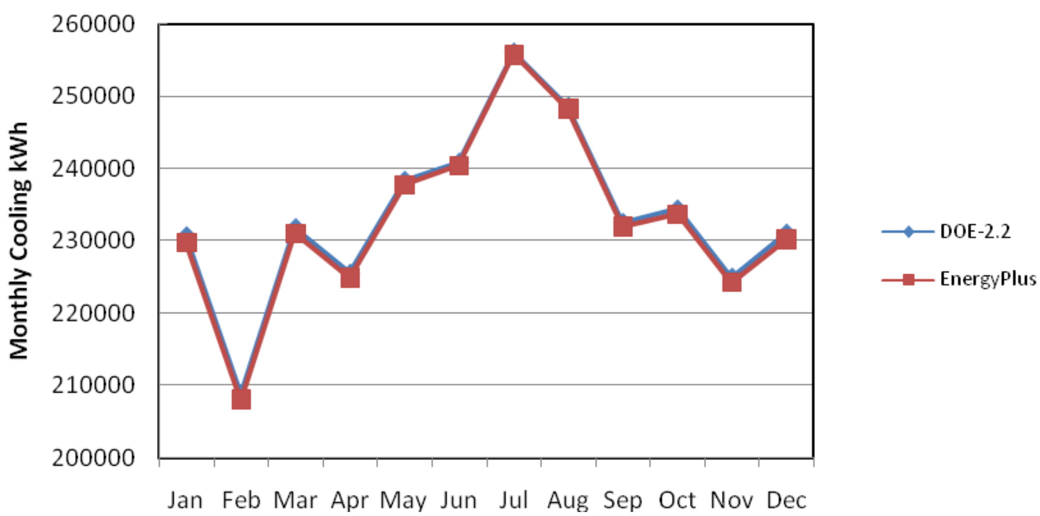

Figure 5 – Monthly Cooling Electricity Consumption for Chicago Runs without Air Economizer

Table 7 - Monthly Cooling Electricity Consumption for Chicago Runs with Air Economizer

	Cooling Electricity Consumption (kWh)		
Month	DOE-2.2	EnergyPlus	% Difference
Jan	0	0	na
Feb	0	0	na
Mar	3,750	3,452	-7.9%
Apr	12,395	11,160	-10.0%
May	84,236	83,272	-1.1%
Jun	175,683	177,715	1.2%
Jul	230,747	231,706	0.4%
Aug	217,651	218,614	0.4%
Sep	138,564	140,582	1.5%
Oct	47,180	46,897	-0.6%
Nov	6,816	6,400	-6.1%
Dec	0	0	na

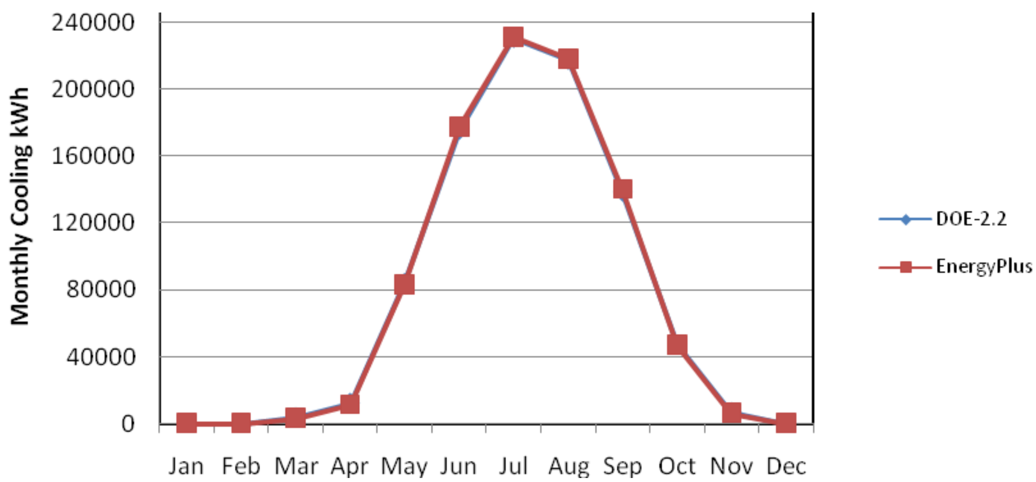

Figure 6 – Monthly Cooling Electricity Consumption for Chicago Runs with Air Economizer

Table 8 - Monthly Cooling Electricity Consumption for Phoenix Runs without Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	235,344	233,591	-0.7%
Feb	212,961	211,382	-0.7%
Mar	244,029	242,394	-0.7%
Apr	246,471	245,010	-0.6%
May	270,454	269,249	-0.4%
Jun	296,797	296,210	-0.2%
Jul	313,155	314,376	0.4%
Aug	306,633	307,593	0.3%
Sep	279,948	280,242	0.1%
Oct	256,685	255,450	-0.5%
Nov	234,478	232,940	-0.7%
Dec	235,204	233,436	-0.8%

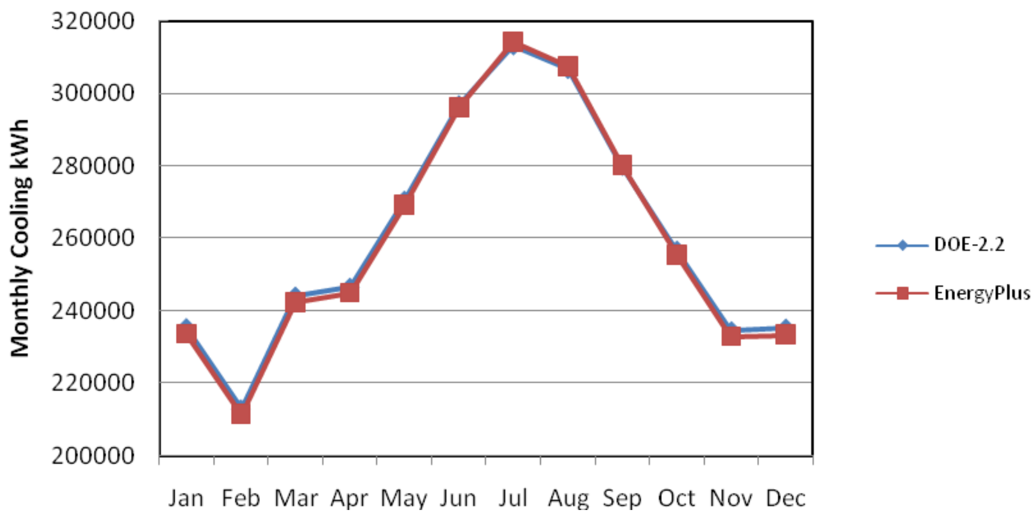

Figure 7 – Monthly Cooling Electricity Consumption for Phoenix Runs without Air Economizer

Table 9 - Monthly Cooling Electricity Consumption for Phoenix Runs with Air Economizer

Month	Cooling Electricity Consumption (kWh)		
	DOE-2.2	EnergyPlus	% Difference
Jan	34,071	30,373	-10.9%
Feb	40,774	36,666	-10.1%
Mar	122,727	120,536	-1.8%
Apr	165,687	162,529	-1.9%
May	230,357	229,335	-0.4%
Jun	290,558	292,574	0.7%
Jul	312,853	314,154	0.4%
Aug	306,608	307,573	0.3%
Sep	274,059	276,362	0.8%
Oct	189,117	192,594	1.8%
Nov	96,738	97,417	0.7%
Dec	33,641	31,445	-6.5%

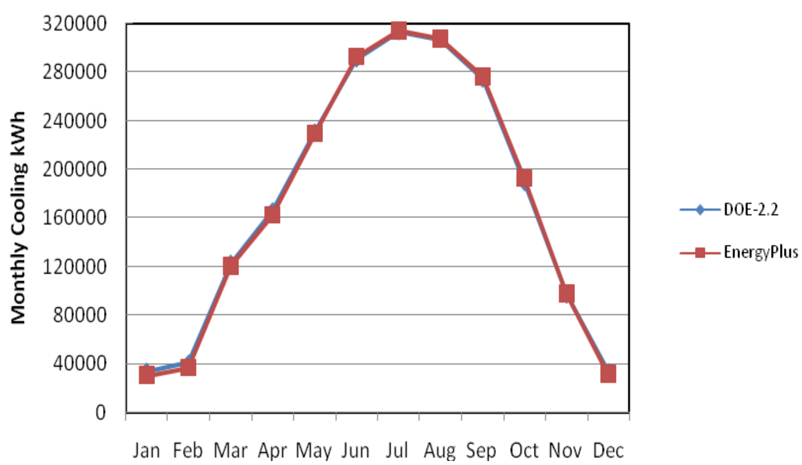

Figure 8 – Monthly Cooling Electricity Consumption for Phoenix Runs with Air Economizer

Results Analysis

For all 16 simulation runs, the annual equipment electric consumptions match exactly. For all 8 EnergyPlus runs, the annual supply fan electric consumption is higher by about 0.2% than DOE-2.2 runs. This is probably due to rounding of fan power inputs for EnergyPlus. Except for the two San Francisco runs with air economizer that show EnergyPlus has 8.6% higher of annual cooling electric consumption than DOE-2.2 result, all other runs demonstrate that annual cooling electric consumption between EnergyPlus and DOE-2.2 runs are very close, within a range of -0.3 to 0.4%.

The without economizer runs, for example the San Francisco runs graphed in Figure 1, show some strange up and down variations of monthly cooling electric consumption – January is high, February is low, March is high, April is low, and so on. Two factors have impact on monthly cooling electricity consumption: the outside air temperature conditions that change the DX cooling efficiency, and the number of days in a month. The latter seems to play a more important role in this case – January has more days than

February, March has more days than April, and so on. As the number of days in each month varies, the monthly total is not adequate to represent the daily variations. Take San Francisco runs as an example, Figure 1 can be reformulated as Figure 9 which shows the normalized average daily cooling kWh with higher consumption in summer and lower consumption in winter. Note that 98% of the cooling kWh is not weather dependent (seasonal kWh fluctuation is in a very tight range).

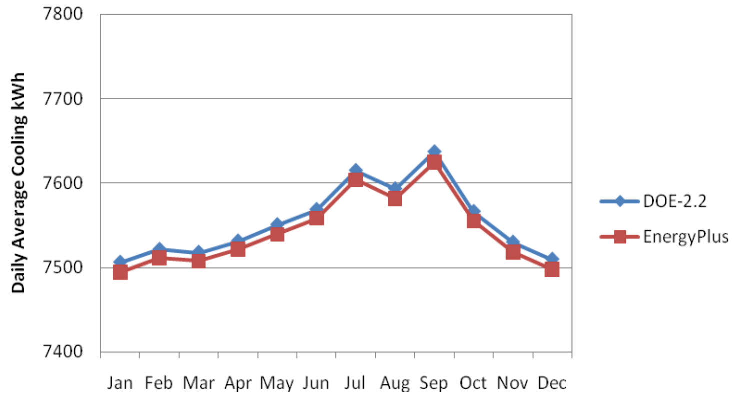

Figure 9 – Average Daily Cooling Electric Consumption kWh for SF Runs without Air Economizer

DX COOLING COIL MODELS

EnergyPlus uses object COIL:DX:CoolingBypassFactorEmpirical to model DX cooling coil which is similar to DOE-2.2 DX coil model but not exactly the same. The CoolingBypassFactorEmpirical DX coil model uses performance data at rated conditions along with performance curve fits for variations in total capacity, energy input ratio and part-load fraction to determine performance at part-load conditions. Sensible/latent capacity splits are determined by the rated sensible heat ratio and the apparatus dew point/bypass factor (ADP/BF) approach. This approach is analogous to the NTU-effectiveness calculations used for sensible-only heat exchanger calculations, extended to a cooling and dehumidifying coil. The DX cooling coil inputs require the rated total cooling capacity, the rated sensible heat ratio, the rated COP, and the rated air flow rate. These four inputs determine the coil performance at the ARI rating conditions: air entering the cooling coil at 26.7°C (80°F) dry-bulb/19.4°C (67°F) wet-bulb and air entering the outdoor condenser coil at 35°C (95°F) dry-bulb/23.9°C (75°F) wet-bulb.

Compared with the DOE-2.2 DX coil model with inputs listed in Table 10, EnergyPlus DX coil model does not use performance curves for the sensible cooling capacity or bypass factor under non-rated conditions. Instead EnergyPlus uses the ADP/BF approach which eliminates the uncertainty and errors associated with the use of performance curves for both the total and sensible cooling capacity.

Table 10 – Comparisons of Air-cooled DX Cooling Coil Models between DOE-2.2 and EnergyPlus

User Inputs	DOE-2.2 DX Coil	EnergyPlus DX Coil
Under ARI rated conditions: Outdoor dry-bulb 95°F, entering dry-bulb 80°F and wet-bulb 67°F.		
Rated Cooling Efficiency	Yes. EIR = 1 / COP	Yes. COP
Rated Total Cooling Capacity	Yes	Yes
Rated Sensible Cooling Capacity	Yes	No
Rated Sensible Heat Ratio	No	Yes
Rated Bypass Factor	Yes	No
Rated Air Flow Rate	Yes	Yes
Curves to describe DX coil operating performance under non-rated and part-load conditions		
Cool-Cap-fEWB&OAT (Total cooling capacity as a function of entering wet-bulb and outdoor air dry-bulb temperatures)	Yes	Yes
Sens-Cap-fEWB&OAT (Sensible cooling capacity as a function of entering wet-bulb and outdoor air dry-bulb temperatures)	Yes	No
Cool-EIR-fEWB&OAT (Cooling efficiency as a function of entering wet-bulb and outdoor air dry-bulb temperatures)	Yes	Yes
Cool-EIR-fPLR (Cooling efficiency as a function of part-load ratio)	Yes	Yes
Bypass-Factor-fAirFlow (Bypass factor as a function of air flow ratio)	Yes	No
Bypass-Factor-fEWB&EDB (Bypass factor as a function of entering wet-bulb and dry-bulb temperatures)	Yes	No
RATED-CCAP-FCFM (Cooling capacity as a function of air flow ratio)		Yes
RATED-CEIR-FCFM (Cooling efficiency as a function of air flow ratio)		Yes

SUMMARY AND DISCUSSION

EnergyPlus is able to produce close results to DOE-2.2 for data centers located in the four climate zones with packaged DX air–cooled systems with and without air economizer. Even due to different DX coil models and different time steps used by EnergyPlus and DOE-2.2, this paper shows consistent results between EnergyPlus and DOE-2.2. Part of the reason is the data center has a relatively constant load which filters complexity from the differences between EnergyPlus and DOE-2.2.

To get apples-to-apples comparisons with better accuracy between EnergyPlus and DOE-2.2 runs, the following guidelines may help:

- Match energy models as close as possible – using same HVAC equipment sizes, fan power, fan layout, cooling efficiency, operation schedules, economizer type and settings, and amount of outside air flow.
- Use same weather data. Tools are available to convert weather data used between EnergyPlus and DOE-2.2.
- Set DOE-2.2 zone thermostat throttling range to a small number say 0.2°F (0.1°C), because EnergyPlus assumes ideal thermostat control and does not use throttling range.
- Use same or similar algorithms for HVAC components if available.

- Pay attention to DOE-2.2 defaults. DOE-2.2 uses numerous implicit BDL defaults which may need to be explicitly converted to EnergyPlus inputs. Add DOE-2.2 command 'DIAGNOSTIC CAUTIONS COMMENTS ..' to DOE-2.2 input files so that default values of applicable DOE-2.2 keywords will be printed in the BDL files with diagnostic messages.

- Use same or equivalent HVAC equipment performance curves. DOE-2 performance curves can be converted for EnergyPlus use either manually or with the CoeffConv tool. DOE-2.2 command CURVE-FIT allows the use of data points or coefficients together with a lower and a higher limit of the curve value (OUTPUT-MAX and OUTPUT-MIN). The CURVE-FIT command does not allow inputs of lower and/or higher limits of dependent curve variables. For EnergyPlus, the CURVE object works the other way: it allows inputs of the minimum and maximum values of the dependent variables, but does not allow inputs of the minimum or maximum value of curve output. When converting DOE-2.2 performance curves into EnergyPlus, convert the implicit minimum and maximum of independent variables as well. For example the DOE-2.2 keyword COOL-FT-MIN sets a minimum of outside dry-bulb temperature 70^{o}F (21.1^{o}C) which is the cut-off temperature for the curves referenced by keywords COOL-CAP-FT, COOL-EIR-FT, and COOL-SH-FT. This is the minimum extrapolation point. As the outside dry-bulb temperature drops below this point the accuracy of the three curves is degraded. DOE-2.2 assumes that the second dependent variable in each of the three curves remains constant at all outside dry-bulb temperatures below COOL-FT-MIN. DOE-2.2 assumes that the corresponding cut-off entering wet-bulb temperature is 60^{o}F (15.6^{o}C).

- Review models with quality controls. Not only look at the annual end uses, but also look at the monthly energy use patterns to help identify gaps and issues.

RECOMMENDATIONS ON FUTURE WORK

Future work, if funding is available, shall expand this comparison study to other design alternatives of data centers:

- Supply air temperature of 75^{o}F (23.9^{o}C). This will reduce the cooling energy due to the increase of the DX cooling efficiency and more air economizer cooling hours, but the supply fan energy will increase and humidity may be an issue.

- DX cooling with water-cooled or evaporatively-cooled condensers

- Chilled water based cooling systems with primary only or primary/secondary pumping

- Chilled water cooling systems with and without water economizer

- Variable air volume systems

- Multiple CRAC units for the data center

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REFERENCES

CEC. 2004. Nonresidential alternative calculation approval manual for the 2005 building energy efficiency standards. Sacramento, California: California Energy Commission.

Crawley, D.B., J.W. Hand, M. Kummert, and B.T. Griffith. 2005. Contrasting the capabilities of building energy performance simulation programs. Building Simulation 2005, Montreal, Canada.

Hirsch and Associates. 2007. DOE-2.2 Documentation Volume 6 – New Features, Versions 41-45.

Huang, J., N. Bourassa, F. Buhl, E. Erdem, and E. Hitchcock. 2006. Using EnergyPlus for California Title-24 Compliance Calculations. Report LBNL-61527. Berkeley, California: Lawrence Berkeley National Laboratory.

LBNL. 1993. DOE-2.1E BDL Summary. Berkeley, California: Lawrence Berkeley National Laboratory.

LBNL. 1982. DOE-2.1A Engineers Manual. Berkeley, California: Lawrence Berkeley National Laboratory.

PG&E. 2006. High Performance Data Centers – A Design Guidelines Sourcebook. San Francisco, California: Pacific Gas and Electric Company.

USDOE. 2007. EnergyPlus 2.1 Input Output Reference Manual. Washington, DC: US Department of Energy.

USDOE. 2007. EnergyPlus 2.1 Engineering Manual. Washington, DC: US Department of Energy.